Conferences and Reviews

Excimer Laser Refractive Surgery

EDWARD E. MANCHE, MD, *Stanford, California*; JONATHAN D. CARR, MD, *Atlanta, Georgia*; WELDON W. HAW, MD, *Stanford, California*; *and* PETER S. HERSH, MD, *Newark, New Jersey*

Review stimulated by publication of the epitome Photoreactive Keratectomy, *(McDonnell PJ, THE WESTERN JOURNAL OF MEDECINE, February 1997;166:139–140)*

Excimer laser photorefractive keratectomy and excimer laser in situ keratomileusis are relatively new treatment modalities that can be used to correct refractive errors of the eye. They are most commonly used to correct myopia (nearsightedness) but can also be used to correct hyperopia (farsightedness) and astigmatism. The excimer laser alters the refractive state of the eye by removing tissue from the anterior cornea through a process known as photoablative decomposition. This process uses ultraviolet energy from the excimer laser to disrupt chemical bonds in the cornea without causing any thermal damage to surrounding tissue. The modified anterior corneal surface enables light to be focused on the retina, thereby reducing or eliminating the dependence on glasses and contact lenses. We discuss in detail all aspects of excimer laser refractive surgery—techniques, indications and contraindications, clinical outcomes, and complications.

(Manche EE, Carr JD, Haw WW, Hersh PS. Excimer laser refractive surgery. West J Med 1998; 169:30–38)

Substantial refractive errors are present in nearly 50% of the US population. Refractive errors cause objects of regard to be focused either in front of or behind the retina and result in blurred vision. These refractive errors are typically corrected with either glasses or contact lenses. About 25% of the population is nearsighted (myopic), and about 20% is farsighted (hyperopic).[1] Most of the population has no substantial refractive error (emmetropic). About 30% of eyes with refractive errors also have some degree of astigmatism.[1]

In myopia, the optical power of a resting (unaccommodating) eye is too strong, and the light rays from a distant object are focused to a point in front of the retina (Figure 1). In hyperopia, the optical power of a resting (unaccommodating) eye is too weak, and the light rays from a distant object are focused to a point behind the retina (Figure 2). In emmetropia, the optical power of a resting (unaccommodating) eye is perfect, and the light rays from a distant object are focused directly onto the retina (Figure 3). In eyes with astigmatism, the situation is slightly more complex. In astigmatism, the anterior refracting surface of the eye is slightly elliptical rather than spherical. This causes light rays from a distant object to come into focus at two discrete points in the eye (Figure 4).

Currently, two types of excimer laser surgery are being used to reshape the cornea and thereby change the refractive power of the eye. The first procedure is photorefractive keratectomy (PRK), which involves the use of an excimer laser to reshape the anterior corneal surface.[2] The PRK procedure is commonly used to correct myopia and astigmatism. Outside the United States, PRK has also been used to correct hyperopia, and clinical trials are currently underway in the United States. In laser in situ keratomileusis (LASIK), the excimer laser is used to reshape the cornea under a corneal flap. In this review, we discuss in detail all aspects of excimer laser refractive surgery, including techniques, indications, contraindications, clinical outcomes, and complications.

Excimer Laser Principles

The excimer laser is based on the combination of two gases: a noble gas and halogen. These gases are stable in their normal low-energy state. When a high-voltage electrical discharge is delivered in a laser cavity containing these gases, however, the gases combine to form a higher-energy excited–gas state compound. The term "excimer" is derived from a contraction of "excited dimer." On the

From the Departments of Ophthalmology, Stanford University School of Medicine, Stanford, California (Drs Manche and Haw); Emory University School of Medicine, Atlanta, Georgia (Dr Carr); and the University of Medicine and Dentistry of New Jersey–New Jersey Medical School, Newark, New Jersey (Dr Hersh).

Reprint requests to Edward E. Manche, MD, Department of Ophthalmology, Stanford University School of Medicine, 300 Pasteur Dr, Rm A157, Stanford, CA 94305-5308.

ABBREVIATIONS USED IN TEXT

D = diopters
LASIK = laser in situ keratomileusis
PRK = photorefractive keratectomy

dissociation of this high-energy compound, a photon of energy is released that corresponds to the bond energy of the noble gas-halogen molecule. This wavelength of light energy is amplified in the laser system and results in the production of a high-energy discrete pulse of laser energy. The specific wavelength of an excimer laser depends on the composition of the gases used in the laser system. The current excimer laser systems use argon and fluorine gases. The argon-fluorine excimer lasers emit energy at a wavelength of 193 nm. This wavelength falls in the UV-C range of the light spectrum. In contrast, the krypton-fluoride excimer laser used in early laboratory studies emits a wavelength of 248 nm.[3,4]

The 193-nm excimer laser energy is well absorbed by the proteins, glycosaminoglycans, and nucleic acids that make up the cornea. Because a 193-nm photon is of higher energy than the molecular bond strength of these compounds, absorption of the laser energy results in a breaking of the bonds. The molecular fragments that thus result are ejected from the surface of the cornea at supersonic speeds. The excimer laser tissue removal process is termed "ablative photodecomposition," and it involves the removal of tissue from the corneal surface, rather than cutting tissue like a scalpel. When this procedure is used clinically, the ablated tissue appears as an effluent plume. Analysis of this plume has shown it to comprise a variety of high-molecular-weight hydrocarbons.[5]

Currently approved lasers have beam diameters of 6.0 to 6.5 mm. Wherever this broad beam impinges on tissue, molecular bonds will be broken and tissue removed. Hence, relatively large areas of the cornea can be treated with each pulse. The excimer laser technique is, thus, qualitatively different from refractive surgical techniques such as radial keratotomy, which achieves corneal reshaping through biomechanical changes mediated through thin knife incisions.

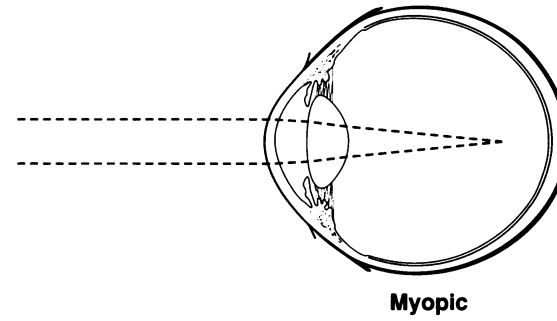

Figure 1.—The ray diagram of a myopic eye shows that the refracting power of the eye is too strong. The light rays from a distant object focus to a point in front of the retina.

Several attributes of the argon-fluoride excimer laser ablation make it particularly appropriate for corneal sculpting. The laser energy is well absorbed near the corneal surface and, thus, should have few deep direct or secondary mechanical (shock-wave) effects on the corneal tissue. The ablation process is rapid, and excess energy is ejected with the effluent plume.[6] There is minimal thermal damage to the surrounding tissue. Because of these qualities, the 193-nm excimer laser can be used to meticulously reshape large areas of the corneal surface while minimizing damage to remaining tissue.[4]

Although apparently relatively little "collateral" damage occurs to the corneal tissue with excimer laser treatment, corneal wound healing remains a major variable affecting clinical outcomes. Corneal wound healing includes epithelial healing over the ablated area[7] and new collagen synthesis in the superficial stroma in the area of photoablation.[8] Such wound healing likely accounts for between-patient variation in treatment results. The corneal wound healing that does occur appears to result in acceptable clinical outcomes.

There is concern about the potential for mutagenesis or carcinogenesis with any laser radiation, especially in

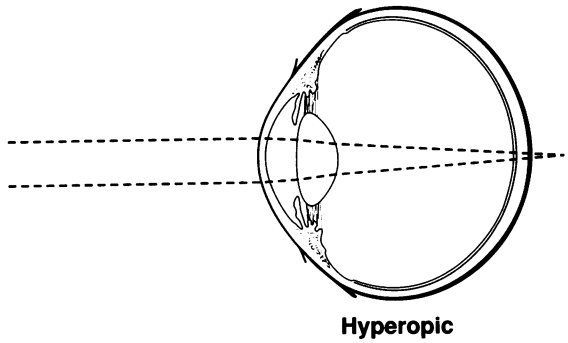

Figure 2.—The ray diagram of a hyperopic eye shows that the refracting power of the eye is too weak. The light rays from a distant object focus to a point behind the retina.

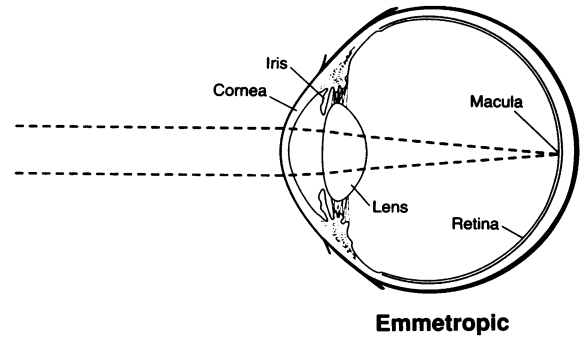

Figure 3.—The ray diagram of an emmetropic eye shows that the refracting power of the eye is perfect. The light rays from a distant object focus directly on the retina.

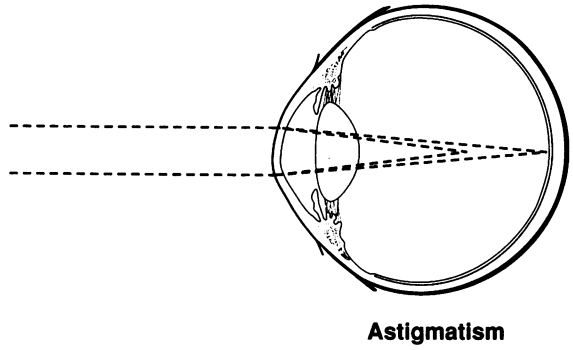

Figure 4.—The ray diagram of an astigmatic eye shows that in astigmatism, the anterior refracting surface of the eye is slightly elliptical rather than spherical. This causes light rays from a distant object to focus at 2 discrete points in the eye.

TABLE 1.—*Advantages and Disadvantages of Laser In Situ Keratomileusis Versus Photorefractive Keratectomy (PRK)*

Advantages
Rapid visual rehabilitation
Minimal pain or discomfort
Low incidence of haze
Intact Bowman's membrane and epithelium
More predictable with high levels of myopia
Disadvantages
More serious potential complications
More difficult to perform than PRK
Steep surgical learning curve
More costly
Possible maintenance problems with instrumentation

the ultraviolet light spectrum. Studies have been done showing that the 193-nm excimer laser is neither mutagenic nor carcinogenic.[9,10] This may be in part a result of shielding of the nucleus by the cell's cytoplasm.

Indications and Contraindications for PRK and LASIK

Currently, the use of PRK and LASIK to treat low to moderate myopia is approved in the United States. This includes for patients older than 18 years with refractive errors ranging from (1.0 to (12.0 diopters (D) of myopia. As much as 4 D of astigmatism can be corrected at the same time. Studies of PRK and LASIK for the treatment of moderate and high myopia are currently ongoing.

Preoperative patient evaluation is of utmost importance in determining eligibility for the PRK and LASIK procedures. Such an evaluation should include multiple refractions and a complete refractive history. Both subjective and cycloplegic refractions should be obtained, and the surgeon must be assured that the refraction is stable. This can be ascertained by reviewing the patient's medical record, inspecting old glasses, and checking refraction more than once.

A thorough medical and ocular history and a complete ocular examination are necessary to ensure the selection of suitable candidates for PRK and LASIK. Systemic conditions that are an absolute contraindication for PRK and LASIK include collagen vascular diseases such as rheumatoid arthritis, systemic lupus erythematosus, and polyarteritis nodosa because of the risk of inflammatory wound healing following PRK. Relative medical contraindications to PRK and LASIK include immunodeficiency of any cause because of the risk of aberrant wound healing and a predisposition to infection and diabetes mellitus because of the tendency for the refraction to fluctuate with the blood glucose level and a possible difficulty in healing corneal epithelial defects. Pregnant or nursing women are excluded because of possible instability of their refractive error. Eye-specific absolute contraindications include ocular surface disorders with anticipated corneal healing problems such as the Stevens-Johnson syndrome, cicatricial ocular pemphigoid, and prior chemical corneal burns. Patients with keratoconus and other ectatic corneal dystrophies often present to a refractive surgeon because of poor vision with spectacles and contact lenses. These conditions are an absolute contraindication for refractive surgery and should be identified during preoperative screening with the aid of computerized corneal topographic analysis.[11–13] Patients with evolving cataracts should also be excluded if cataract extraction is anticipated because appropriate selection of the intraocular lens power at the time of cataract extraction would obviate the need for PRK and LASIK. A history of herpes simplex keratitis is a relative contraindication because of the risk of the reactivation of keratitis following PRK and LASIK.[14,15]

Further investigation will help to identify preoperative characteristics associated with the outcome of PRK and LASIK. Aging of the patient and higher attempted PRK corrections have been shown to be independent preoperative characteristics associated with less likelihood of 20/40 uncorrected visual acuity and overcorrection postoperatively.[16] Clearly more research in this area is warranted.

Having established a patient's suitability for PRK and LASIK, appropriate informed consent is required, as in any surgical procedure. Such informed consent should delineate both the possible optical (such as glare or halo) and physical (such as scarring) complications of the procedure. The patient should also have a realistic expectation of the refractive outcome and understand that no refractive procedure can absolutely guarantee "perfect" vision.

Mechanisms of Laser Delivery

The clinical excimer laser comprises the following components: gases, power source, laser cavity, beam-forming optics, delivery system, aiming system, and surgical microscope.

For most current excimer laser systems, the initial pulse delivered from the laser cavity is a broad rectangular beam

of irregular energy level. For clinical use, this beam needs to be homogenized to yield a consistent energy over the entire delivery area. In the absence of a smooth and consistent beam energy, ablation rates could vary over the treatment area. In addition, the beam needs to be masked in two dimensions to the appropriate size and shape. Such beam homogenization and shaping are accomplished through a number of beam-shaping optics in the optical train of the laser. In addition, a diaphragm[17] interposed within this optical train masks the beam, causing it to be delivered as a circular spot of chosen diameter.

Current excimer lasers in clinical use operate at energy levels of about 160 to 180 millijoules (mJ) and a pulse rate of 5 to 10 pulses per second. The expected ablation rate of corneal tissue averages approximately 0.25 (m per pulse for a laser operating at 180 mJ per cm^2.[18–20]

To achieve refractive correction, the excimer laser energy is applied to the patient's cornea in a controlled manner to sculpt the appropriate tissue lens from the corneal surface for refractive corrections. This is accomplished in most units by a diaphragm interposed in the optical rail of the system, which expands as the treatment proceeds. Consecutively less tissue is thus removed from the center to the periphery of the ablation zone, with consequent flattening of the corneal surface. The pace of diaphragm opening and the duration of the procedure are determined by variables programmed into the laser's computer control.

Other strategies have been and are currently being developed to sculpt the corneal surface for refractive computer control. An ablatable mask (Summit Technology, Waltham, MA) is a polymethylmethacrylate lens interposed between the laser and the patient.[21–24] This mask is progressively ablated by the incoming laser beam. A concave mask is thus completely ablated centrally before peripherally. As the mask shield to the incoming beam is progressively ablated away, the optical power of the mask is transferred to the corneal surface. A toric mask can also be used to treat myopic astigmatism. Other laser strategies include a small scanning beam (such as Laser Sight , Orlando, FL) or a scanning slit (such as Nidek, Gamagori, Japan) that can be programmed to properly ablate the desired tissue. Strategies for correcting astigmatism include the ablatable mask, expandable slits (correcting cylindrical errors), and elliptical diaphragms for toric ablations. In all such lasers, the goal is to remove a spherocylindrical tissue lens from the corneal surface.

Another important factor in the development of the clinical excimer laser system is the modality of laser-eye coupling. Some investigators initially used a variety of handheld fixation devices and suction rings to stabilize a patient's eye. The manual fixation techniques have been abandoned, and the procedure is performed using simple patient fixation, directing the patient to fixate on a target coaxial with the incoming laser beam. Self-fixation yields better centration of the procedure than does actual physical fixation of the eye.[25] More recently, laser-eye coupling has been achieved by a variety of eye-tracking devices that have been developed to allow the laser to follow the eye in real time, thus minimizing the effects of eye movements during the procedure.

PRK Procedure and Postoperative Management

Preoperatively, the operative eye is labeled, and the contralateral eye is patched. This is to ensure that the patient maintains fixation with the operative eye and does not inadvertently fixate with the fellow eye. The refractive correction is confirmed. Mild sedation may be given to the patient before the operation. The patient is positioned on the excimer laser chair. A topical anesthetic is applied in multiple applications, and then a lid speculum is placed. The surgeon should ensure that the patient is comfortable and able to cooperate during the treatment. The patient is then properly aligned under the microscope of the excimer laser. In general, the patient is asked to fixate on a light that is coaxial with the incoming laser beam. The patient should then be reassured about the snapping sound of the laser and the odor associated with the ablation of corneal tissue. A round optical zone marker is used to mark the border of epithelium to be debrided. The epithelium is then carefully removed using one of a variety of methods, including manual scraping, rotating brushes, or the excimer laser itself (transepithelial technique). With all techniques, care is taken not to damage Bowman's layer. Moreover, the basal epithelial cells must be meticulously removed because residual epithelium would block the incoming beam and lead to uneven ablation. On the removal of epithelium—generally about 7 mm in diameter to accommodate a 6.0- to 6.5-mm laser optical zone size—centration is assured and the foot pedal of the laser depressed. A typical treatment may take approximately 200 laser pulses, 20 seconds at 10 Hz or 40 seconds at 5 Hz.

At the end of the procedure, a combination antibiotic and steroid solution, a topical nonsteroidal drop, and a bandage contact lens are placed in the patient's eye. The use of topical nonsteroidal anti-inflammatory agents and soft contact lenses have been shown to decrease postoperative pain following PRK.[26] Patients may be given oral nonsteroidal agents or narcotics and sleeping medications to make their first night comfortable. The patient is observed closely until the epithelium is healed, generally by 72 hours. On epithelial healing, a tapering regimen of corticosteroids is generally used for the first several months. The necessity and appropriate use of steroids remains a matter of controversy. A randomized double-masked study of the use of topical corticosteroid after PRK failed to show a sustained benefit compared with placebo after the cessation of therapy.[27] Other authors, however, have reported a significant role for topical corticosteroids in modulating postoperative wound healing.[28] Further studies may clarify the specific role of topical corticosteroid use in the postoperative management of PRK.

Clinical Results

The excimer laser underwent extensive clinical studies in the United States for about six years before receiving

approval by the Food and Drug Administration in October 1995. The initial studies focused on the correction of myopia in the range of 1.0 to 7.75 D.[29–31] Other investigators have looked at the use of the excimer laser for the correction of higher myopia[32–38] and astigmatism.[21,23,39–41] For a refractive procedure such as PRK, there are four important indices of outcome: the likely postoperative uncorrected visual acuity and predictability, stability, and safety of the procedure.

A general review of the literature shows uncorrected visual acuity following PRK in patients with lower degrees of myopia to range from 80% to 95% of patients with uncorrected visual acuity of 20/40 or better and 50% to 70% of patients at 20/20 or better. Recent studies report better results than investigations in the earlier phases of clinical excimer development, suggesting improvement of the PRK procedure. In phase III clinical trials, for instance, the use of Summit and VISX, Inc. (Santa Clara, CA) resulted in uncorrected visual acuities of 20/40 in more than 95% of eyes.[29–31]

The predictability of PRK is an indication of the refractive accuracy and is usually reported as the percentage of eyes achieving a correction within (0.50 D (or (1.00 D) of the desired refractive correction. For low myopia, about half of patients fall within 0.5 D of attempted correction, about three quarters of patients within 1.0 D, and about 95% of patients within 2 D of attempted correction. Studies of higher degrees of myopia show somewhat less predictability and postoperative uncorrected vision.[32–38]

Stability data for PRK are important for two reasons. The interval between the surgical procedure and a stable refraction allows the determination of the earliest reasonable time when reoperation might be considered for residual refractive errors. The long-term stability data for refractive surgical procedures allow accurate refractive correction with minimal risk of future large changes in refraction. For example, ten-year postoperative radial keratotomy data have shown that a proportion of patients became hyperopic long after their original operation to reduce myopia.[42] Studies of PRK, to date, have not shown this progressive hyperopia effect. In the early wound healing phase, many patients who have had excimer laser therapy regress somewhat, appearing to plateau at a relatively stable correction after about six months. Such stabilization may take longer in patients with higher diopter corrections. Stability and ultimate outcome may be affected by a patient's wound healing pattern. Most patients follow the typical pattern of slight regression early in the course, with subsequent stabilization. Better understanding of the individual wound healing response may suggest pharmacologic interventions to modulate the outcome following PRK.

Safety is typically reported as the percentage of eyes losing two or more lines of best spectacle-corrected visual acuity on the Snellen chart as the result of surgical treatment. In a recent report of the outcome of PRK for low, moderate, and high myopia in 504 eyes,[36] for myopia below (5.00 D, 4% of eyes lost two or more lines of best-corrected visual acuity; for myopia of between (5.00 and (10.00 D, 8% of eyes lost two or more lines; and for PRK above (10.00 D, 22% of eyes lost two or more lines of best spectacle-corrected visual acuity. The increased loss of best-corrected visual acuity observed with PRK corrections of high myopia is usually attributed to scarring. Future refinements in PRK laser ablation may reduce the likelihood of this complication.

Excimer laser PRK has also been used following other refractive surgical procedures such as radial keratotomy. Eyes with residual refractive errors following refractive keratotomy have been treated with the excimer laser to achieve better correction. In a large, prospective, multicenter clinical trial to evaluate the safety and efficacy of PRK following previous refractive surgery (primarily refractive keratotomy),[43] there was a high incidence of postoperative corneal scarring and loss of best spectacle-corrected visual acuity. Consequently, PRK should probably not be performed in eyes previously treated with refractive keratotomy.

Complications

Complications of refractive surgical procedures such as PRK and LASIK can be considered primarily optical or "physical." Optical complications include glare, halo, decreased contrast sensitivity, and diplopia. Glare and halo symptoms are likely due to the optical effects of light passing through the border between centrally treated and peripherally untreated cornea. An eye with a larger pupil would be more likely to manifest the symptoms of glare and halo, especially at night when the pupillary diameter is greatest.

Physical complications of PRK and LASIK include scarring, microbial keratitis, and sterile keratitis (infiltrates). Some degree of corneal wound healing after PRK is indicative of anticipated corneal wound healing. More substantial haze and scarring indicate aggressive wound healing and may lead to the regression of effect and loss of best spectacle-corrected visual acuity, as well as optical effects such as decreased contrast sensitivity, diplopia, glare, and halo. Corneal haze typically decreases during the first 12 months following PRK. Microbial keratitis is an unlikely complication of refractive surgical procedures in general and has been reported to occur in 1 of 2,400 cases of refractive keratotomy.[44] It requires immediate culture of corneal scrapings and intensive topical therapy with fortified broad-spectrum antibiotics. Scarring following the resolution of infection may limit best spectacle-corrected visual acuity and might in theory require corneal transplantation. Since the use of soft contact lenses and topical nonsteroidal anti-inflammatory medications to ameliorate pain during the initial 72 hours after PRK, the occurrence of sterile infiltrates has been reported,[26,45,46] which poses a diagnostic dilemma to ophthalmologists. Therapy for such sterile infiltrates includes the use of topical corticosteroids, which might exacerbate a case of unrecognized microbial keratitis. It is imperative, therefore, that microbial keratitis be ruled

out before the use of topical corticosteroids is contemplated for postoperative subepithelial infiltrates.

Correction of Astigmatism

Multiple studies have demonstrated the safety and efficacy of using the excimer laser to correct myopic astigmatism.[47–55] This procedure is labeled toric PRK or photoastigmatic refractive keratectomy and involves preferential reshaping of the cornea along a specified axis by either a nonspherical (elliptical) ablation or an ablatable mask. With current nomograms, 44% to 94% of cases of astigmatism can be corrected,[47–49,51–53] and 55% to 93% of eyes have an uncorrected visual acuity of 20/40 or better.[47,48,51–56]

In a Food and Drug Administration phase III clinical trial evaluating the safety and efficacy of photoastigmatic keratectomy using the Summit Apex Plus excimer laser in 93 eyes, a 90% reduction in compound myopia (spherical equivalent) and a 64% reduction in myopic astigmatism were seen at one-year follow-up.[56] In these patients, 81% of eyes were within 1.0 D of attempted correction, and 93% had an uncorrected visual acuity of 20/40 or better. Five percent lost more than two lines of best spectacle-corrected visual acuity. All eyes with haze had 20/20 or better best-corrected visual acuity. Contrast sensitivity function was temporarily diminished but returned to preoperative levels by 6 to 12 months.[57]

Excimer Laser In Situ Keratomileusis

During recent years, LASIK has become the procedure of choice for moderate to high levels of myopia among refractive surgeons. This procedure combines the developments made in lamellar surgery during the past 50 years with the technology and accuracy of the excimer laser. It involves the use of a microkeratome to create a superficial corneal flap, subsequent stromal ablation of the exposed corneal bed with the excimer laser, and repositioning of the corneal flap.

Historically, the foundation for LASIK is largely credited to Jose Ignacio Barraquer, MD. In the late 1940s, Barraquer performed freehand lamellar dissection in conjunction with the excision of stroma . Since then, many refinements have been made in lamellar surgery, including the use of the automated microkeratome and the development of the excimer laser. In 1988, Pallikaris initiated the use of the excimer laser in studies on rabbit eyes.[58] This led to his investigation of the laser in sighted human eyes in 1991. Many recent studies have demonstrated the effectiveness of LASIK in reducing myopia.[59–75] Currently, LASIK is performed on hundreds of thousands of people with myopia worldwide.

Patient Selection

Typically, LASIK had been used for moderate to high levels of myopia (4.0 to 16.0 D) in which PRK may yield suboptimal results. With improvements in surgical techniques and stable visual outcomes reported following LASIK, however, it is now being successfully used by many refractive surgeons to treat the low-level range of myopia as well.[61,62] As with PRK, patients must be older than 18 years, demonstrate stability in cycloplegic refraction for at least 12 months, and have a central corneal thickness not less than 500 (m for myopia less than 10 D and not less than 550 (m for myopia of 10 to 16 D. Patients with as much as 7.0 D of hyperopia and 7.0 D of astigmatism may also be candidates.[65]

Absolute contraindications include eyes with corneal disorder in shape, thickness, or inflammatory status. Thus, eyes with keratoconus; corneal ectasias; and corneas that are thin, active, or that have been recently inflamed (that is, with herpetic keratitis) should be excluded. Relative contraindications include patients with systemic vasculitis, autoimmune disease, collagen disorders, and diabetes mellitus or other states with abnormal healing. In addition, in monocular patients, patients with unstable precorneal tear film such as in the sicca syndrome, and those with endothelial counts of less than 1,500 cells, the procedure should also be considered as relatively contraindicated.

Technique

After patient education and informed consent, a topical antibiotic drop and a topical anesthetic (proparacaine hydrochloride, 0.5% solution) are placed in the eye. After the patient is prepared and draped, a wire-lid speculum is placed in the operated eye. A LASIK marker is used to facilitate appropriate realignment of the flap. A LASIK pneumatic suction ring is placed on the eye, and the intraocular pressure is raised to greater than 65 mm of mercury. The microkeratome is positioned on its tracks and used to resect a 130- to 180-(m corneal flap with a 300-degree circumference. Depending on the type of microkeratome, the corneal flap may be hinged along the nasal or superior border of the cornea.

Using a spatula or a forcep, the flap is elevated along its hinged border, and the excimer laser is used to photoablate the stromal bed. The stromal bed is irrigated with an isotonic sodium chloride solution, and the flap is reapproximated using the corresponding epithelial markings of the flap and the limbus created by the LASIK marker. Drying the cut edges and allowing the cornea to set for approximately 2 to 5 minutes allows the flap to adhere to the underlying stromal bed without the need for sutures. The lid speculum and drapes are removed, and the adherence of the flap is assessed by asking the patient to blink.

Postoperatively, patients may wear a transparent eye shield and are asked to refrain from rubbing their eyes. They are given a short course of topical broad-spectrum antibiotics, topical steroids, and artificial tears. Patients are observed on the first postoperative day and regularly thereafter at the discretion of the refraction surgeon.

Clinical Results

Early Summit phase I investigations on excimer laser myopic keratomileusis yielded promising results. In six-month results on 47 eyes, 16 (34%) had an uncorrected

visual acuity of 20/25 or better, and 31 (66%) had 20/40 or better.[75] Since then, several recent studies have demonstrated the safety, stability, predictability, and efficacy of LASIK in reducing myopia.[59–75] With current technology and nomograms, uncorrected visual acuity on the first day following the surgical procedure is 20/40 or better in 86% of patients with low myopia and astigmatism.[60] With longer follow-up, a review of current literature demonstrates an uncorrected visual acuity of 20/20 or better in 30% to 80%[60,62,63,71,74] of eyes and 20/40 or better in about 70% to 90% of eyes.[60,62,74] The results vary depending on the level of preoperative myopia.[65]

Because LASIK is typically used to correct higher levels of myopia, consideration of the preoperative level of myopia and attempted correction should be noted before comparing results of PRK with those of LASIK in the current literature. In a recent study comparing PRK with LASIK in the treatment of low to moderate amounts of myopia ((1.25 to –6.00 D), at one-year follow-up, 83% (85/103 eyes) of eyes undergoing LASIK had an uncorrected visual acuity of 20/20 compared with 72% (221/307 eyes) of eyes treated with PRK.[63]

Predictability is also an important indicator of refractive surgical outcome. With the use of LASIK, 81% to 89% of eyes are within (1.0 D of attempted correction.[59,60,63] Predictability, however, decreases with increasing level of myopia.[62] In higher levels of myopia, 60% to 78% of eyes are within (1.0 D of attempted correction.[59,62,66,68,77]

As with PRK, there may be a subtle loss in contrast sensitivity following LASIK. This is measurable only with rigorous testing. These subtle losses, however, may return to preoperative states 3 months after LASIK and 6 to 12 months after PRK.[62] In addition, there may be some regression (about 0.5 D) within three months after LASIK. Higher levels of myopia may lead to a further regression.[66]

The LASIK procedure offers several advantages over PRK (Table 1). Unlike the extended postoperative recovery period after PRK, there is rapid visual rehabilitation after LASIK. On the first postoperative day following LASIK, 61% to 80% of patients will have uncorrected visual acuity of 20/40 or better, depending on the level of myopia.[58] In addition, patients usually have only mild irritative symptoms or foreign body sensation immediately following LASIK. Unlike with PRK, the incidence of corneal scarring and haze are substantially reduced after LASIK.[71,72]

Complications may occur following LASIK, however. The most common complication is undercorrection. As in any refractive surgical procedure, all patients should be educated about the procedure and have a realistic perception of the surgical outcome. In most cases, retreatment of undercorrection is straightforward and yields good results.[67] The most serious complications can occur during the creation of the corneal flap. Perforation into the anterior chamber with the microkeratome, with resultant intraocular damage to the lens, ciliary body, and iris has been reported. Mechanical complications may also arise: loss of suction, microkeratome malfunction, and poor surgical technique. This can result in a number of flap complications, including an irregular flap, complete excision of the flap with a resultant free flap, too thin a flap, too thick a flap, a buttonholed flap, and wrinkles in the flap. Raising the intraocular pressure during the intraoperative phase may also result in retinal hemorrhages and vein occlusions.

The loss of best spectacle-corrected visual acuity of more than one line of Snellen visual acuity may occur in 0% to 8.8 % of eyes undergoing LASIK.[59,68,72,74,75] This may result from irregular astigmatism, progressive myopic maculopathy, epithelial ingrowth, or other complications.

The limitations of surface refractive techniques such as PRK have led to the evolution of more complicated lamellar surgical procedures such as LASIK. This procedure is technically demanding and has a steep surgical learning curve. In expert hands, however, LASIK may be more effective than PRK in the treatment of moderate to high-level myopia with shorter postoperative visual rehabilitation, earlier stable and predictable outcomes, and less corneal haze.[63,75] Refinements in the microkeratomes, technology, software, and techniques will lead to further improvements in the precision of LASIK for the treatment of refractive error.

Conclusions

Modern excimer laser refractive surgery is an exciting field of medicine that provides ophthalmologists with a tool to lessen or eliminate patients' dependence on glasses and contact lenses. The field is a dynamic one with the introduction of newer, more advanced technology and surgical techniques at a rapid pace. These advances should enable refractive surgeons to treat patients with higher levels of nearsightedness, astigmatism, and hyperopia in the near future. As the technology and techniques improve, we should develop a better understanding of the importance of laser-tissue interactions, corneal wound healing, and the role of pharmacologic agents in modulating refractive outcomes. These advances should allow PRK and LASIK to become more predictable with fewer complications.

REFERENCES

1. Refractive Errors. Preferred Practice Patterns. American Academy of Ophthalmology, San Francisco, California; 1997

2. Trokel SL, Srinivasan R, Braren B. Excimer laser surgery of the cornea. Am J Ophthalmol 1983; 96:710–715

3. Burlamacchi P. Laser sources. In: Hillenkamp F, Pratesi R, Sacchi CA, eds. Lasers in biology and medicine. New York (NY): Plenum Press; 1980:1–16

4. Puliafito CA, Steinert RF, Deutsch TF, Hillenkamp F, Dehm EJ, Adler CM. Excimer laser ablation of the cornea and lens: experimental studies. Ophthalmology 1985; 92:741–748

5. Jellinek HH, Srinivasan R. Theory of etching of polymers by far-ultraviolet, high-intensity pulsed laser and long-term irradiation. J Phys Chem 1984; 88:3048

6. Kahle G, Stadter H, Seiler T, Wollensak J. Gas chromatograph/mass spectrometer analysis of excimer and erbium-YAG laser ablated human corneas. Invest Ophthalmol Vis Sci 1992; 33:2180–2184

7. Tuft SJ, Zabel RW, Marshall J. Corneal repair following keratectomy: a comparison between conventional surgery and laser photoablation. Invest Ophthalmol Vis Sci 1989; 30:1769–1777

8. Malley DS, Steinert RF, Puliafito CA, Dobi ET. Immunofluorescence study of corneal wound healing after excimer laser anterior keratectomy in the monkey eye. Arch Ophthalmol 1990; 108:1316–1322

9. Nuss RC, Puliafito CA, Dehm EJ. Unscheduled DNA synthesis following

excimer laser ablation of the cornea in vivo. Invest Ophthalmol Vis Sci 1987; 28:287–294

10. Kochevar IE. Cytotoxicity and mutagenicity of excimer laser radiation. Lasers Surg Med 1989; 9:440–445

11. Wilson SE, Klyce SD. Screening for corneal topographic abnormalities before refractive surgery. Ophthalmology 1994; 101:147–152

12. Wilson SE. Corneal topography of keratoconus. Cornea 1991; 10:2–8

13. Rabinowitz YS, McDonnell PJ. Computer-assisted corneal topography in keratoconus. J Refract Corneal Surg 1989; 5:400–408

14. Pepose JS, Laycock KA, Miller JK, Chansue E, Lenze EJ, Gans LA, et al. Reactivation of latent herpes simplex virus by excimer laser photokeratectomy. Am J Ophthalmol 1992; 114:45–50

15. Vrabec MP, Anderson JA, Rock ME, Binder PS, Steinert RF, Durrie DS, et al. Electron microscopic findings in a cornea with recurrence of herpes simplex keratitis after excimer laser phototherapeutic keratectomy. CLAO J 1994; 20:41–44

16. Hersh PS, Schein OD, Steinert R. Characteristics influencing outcomes of excimer laser photorefractive keratectomy—Summit Photoreactive Keratectomy Phase III Study Group. Ophthalmology 1996; 103:1962–1969

17. McDonald MB, Frantz JM, Klyce SD, Salmeron B, Beuerman RW, Munnerlyn CR, et al. One-year refractive results of central photorefractive keratectomy for myopia in the nonhuman primate cornea. Arch Ophthalmol 1990; 108:40–47

18. Krueger RR, Trokel SL. Quantitation of corneal ablation by ultraviolet laser light. Arch Ophthalmol 1985; 103:1741–1742

19. Krueger RR, Trokel SL, Schubert HD. Interaction of ultraviolet laser light with the cornea. Invest Ophthalmol Vis Sci 1985; 26:1455–1464

20. Seiler T, Kriegerowski M, Schnoy N, Bende T. Ablation rate of human corneal epithelium and Bowman's layer with the excimer laser (193 nm). J Refract Corneal Surg 1990; 6:99–102

21. Hersh PS, Patel R. Correction of myopia and astigmatism using an ablatable mask. J Refract Corneal Surg 1994; 10 Suppl:250–254

22. Maloney R, Friedman M, Harmon R, Hagen K. A prototype ablatable mask delivery system for the excimer laser. Ophthalmology 1993; 100:542–549

23. Cherry PM, Tutton MK, Bell A, Neave C, Fichte C. Treatment of myopic astigmatism with photorefractive keratectomy using an erodible mask. J Refract Corneal Surg 1994; 10 Suppl:239–245

24. Friedman MD, Bittenson S, Brodsky L, et al. OmniMed II: a new system for use with the emphasis erodible mask. J Refract Corneal Surg 1994; 10 Suppl:267–273

25. Terrell J, Bechara SJ, Nesburn A, Waring GO, Macy J, Maloney RK. The effect of globe fixation on ablation zone centration in photorefractive keratectomy. Am J Ophthalmol 1995; 119:612–619

26. Sher NA, Frantz JM, Talley A, et al. Topical diclofenac in the treatment of ocular pain after excimer photorefractive keratectomy. J Refract Corneal Surg 1993; 9:425–436

27. Gartry DS, Kerr MM, Marshall J. The effect of topical corticosteroids on refraction and corneal haze following excimer laser treatment of myopia: an update—A prospective, randomized double-masked study. Eye 1993; 7(pt 4):584–590

28. Fagerholm P, Hamberg NH, Tengroth B, Epstein D. Effect of postoperative steroids on the refractive outcome of photorefractive keratectomy for myopia with the Summit excimer laser. J Cataract Refract Surg 1994; 20 Suppl:212–215

29. Maguen E, Salz JJ, Nesburn AB, Warren C, Macy JI, Papaioannou T, et al. Results of excimer laser photorefractive keratectomy for the correction of myopia. Ophthalmology 1994; 101:1548–1556

30. Talley AR, Hardten DR, Sher NA, Kim MS, Douighman DJ, Carpel E, et al. Results one year after using the 193-nm excimer laser for photorefractive keratectomy in mild to moderate myopia. Am J Ophthalmol 1994; 118:304–311

31. Dutt S, Steinert RF, Raizman MB, Puliafito CA. One-year results of excimer laser photorefractive keratectomy for low to moderate myopia. Arch Ophthalmol 1994; 112:1427–1436

32. Carson CA, Taylor HR. Excimer laser treatment of high and extreme myopia. Arch Ophthalmol 1995; 113:431–436

33. Cho YS, Kim CG, Kim WB, Kim CW. Multistep photorefractive keratectomy for high myopia. J Cataract Refract Surg 1993; 9 Suppl:37–41

34. Ditzern K, Anschutz T, Schroder E. Photorefractive keratectomy to treat low, medium, and high myopia: a multicenter study. J Cataract Refract Surg 1994; 20 Suppl:234–238

35. Kim HM, Jung HR. Multizone photorefractive keratectomy for myopia of 9 to 14 diopters. J Refract Surg 1995; 11(3 suppl):S293–S297

36. McCarty CA, Aldred GF, Taylor HR. Comparison of results of excimer laser correction of all degrees of myopia at 12 months postoperatively—The Melbourne Excimer Laser Group. Am J Ophthalmol 1996; 121:372–383

37. Rogers CM, Lawless MA, Cohen PR. Photorefractive keratectomy for myopia more than (10 diopters. J Refract Corneal Surg 1994; 10 Suppl:S171–S173

38. Sher NA, Hardten DR, Fundingsland B, DeMarchi J, Carpel E, Doughman DJ, et al. 193-nm excimer photorefractive keratectomy in high myopia. Ophthalmology 1994; 101:1575–1582

39. Taylor HR, Kelly P, Alpins N. Excimer laser correction of myopic astigmatism. J Cataract Refract Surg 1994; 20 Suppl:243–251

40. Spigelman AV, Albert WC, Cozean CH, Johnson DG, McDonnell PJ, Pender PM, et al. Treatment of myopic astigmatism with the 193 nm excimer laser utilizing aperture elements. J Cataract Refract Surg 1994; 20 Suppl:258–261

41. Pender PM. Photorefractive keratectomy for myopic astigmatism: phase IIA of the Federal [sic] Drug Administration study (12 to 18 months follow-up)—Excimer Laser Study Group. J Cataract Refract Surg 1994; 20 Suppl:262–264

42. Waring GO 3d, Lynn MJ, McDonnell PJ. Results of the prospective evaluation of radial keratotomy (PERK) study 10 years after surgery. Arch Ophthalmol 1994; 112:1298–1308

43. Maloney RK, Chan W, Steinert R, O'Connell M. A multicenter trial of photorefractive keratectomy for residual myopia after previous ocular surgery. Ophthalmology 1995; 102:1042–1053

44. Cottingham AJ, Berkeley RG, Nordan LT. Bacterial corneal ulcers following keratorefractive surgery: a retrospective study of 14,163 procedures. Presented at the Ocular Microbiology and Immunology Group Meeting, San Francisco, California, 1986

45. Teal P, Breslin C, Arshinoff S, Edmison D. Corneal subepithelial infiltrates following excimer laser photorefractive keratectomy. J Cataract Refract Surg 1995; 21:516–518

46. Probst LS, Machat JJ. Corneal subepithelial infiltrates following photorefractive keratectomy (Correspondence). J Cataract Refract Surg 1996; 22:281

47. Gallinaro C, Toulemont PJ, Cochener B, Colin J. Excimer laser photorefractive keratectomy to correct astigmatism. J Cataract Refract Surg 1996; 22:557–563

48. Carones F, Brancato R, Morico A, Venturi E, Gobbi PG. Compound myopic astigmatism correction using a mask in-the-rail excimer laser delivery system: preliminary results. Eur J Ophthalmol 1996; 6:221–233

49. Kremer I, Gabbay U, Blumenthal M. One-year follow-up results of photorefractive keratectomy for low, moderate, and high primary astigmatism. Ophthalmology 1996; 103:741–748

50. Kim YJ, Sohn J, Tchah H, Lee CO. Photoastigmatic refractive keratectomy in 168 eyes: six-month results. J Cataract Refract Surg 1994; 20:387–391

51. Goggin MJ, Kenna PF, Lavery FL. Photoastigmatic refractive keratectomy for compound myopic astigmatism with a Nidek laser. J Refract Surg 1997; 13:162–166

52. Hamberg-Nystrom H, Fagerholm PP, Tengroth BM, Viding AV. One year follow-up of photoastigmatic keratectomy (PARK) with the VISX 20/20 excimer laser. Ophthalmic Surg Laser 1996; 27(suppl):S499–S502

53. Tasindi E, Talu H, Ciftci F, Acar S. Excimer laser photorefractive keratectomy (PRK) in myopic astigmatism. Eur J Ophthalmol 1996; 6:121–124

54. Kaskaloglu M. Early results of photorefractive keratectomy for myopic astigmatism. J Refract Surg 1996; 12:S258–S260

55. Snibson GR, Carson CA, Aldred GF, Taylor HR. One-year evaluation of excimer laser photorefractive keratectomy for myopia and myopic astigmatism—Melbourne Excimer Laser Group. Arch Ophthalmol 1995; 113:994–1000

56. Haw WW, Manche EE. Toric PRK using the Summit Apex Plus excimer laser with an erodible mask—Phase III of an FDA clinical trial. Presented at the American Society of Cataract and Refractive Surgery meeting, San Diego, California, April 21, 1998

57. Haw WW, Manche EE. Visual performance following toric PRK using the Summit Apex Plus excimer laser. Presented at the American Society of Cataract and Refractive Surgery meeting, San Diego, California, April 19, 1998

58. Pallikaris IG, Papatzanki ME, Sigamous DS, et al. A corneal flap technique for laser in situ keratomileusis. Human Studies. Arch Ophthamol 1991; 145:1699-1702

59. Lindstrom RL, Hardten DR, Chu YR. Laser in situ keratomileusis (LASIK) for the multicenter phase I treatment of low, moderate, and high myopia. Trans Am Ophthalmol Soc 1997; 95:285–296

60. Zaldivar R, Davidorf JM, Shultz MC, Oscherow S. Laser in situ keratomileusis for low myopia and astigmatism with a scanning spot excimer laser. J Refract Surg 1997; 13:614–619

61. Danasoury MA, Waring GO, Maghraby A; Mehrez K. Excimer laser in situ keratomileusis to correct compound myopic astigmatism. J Refract Surg 1997; 13:511–520

62. Pesando PM, Ghiringhello MP, Tagliavacche P. Excimer laser in situ keratomileusis for myopia. J Refract Surg 1997; 13:521–527

63. Wang Z, Chen J, Yang B. Comparison of laser in situ keratomileusis and photorefractive keratectomy to correct myopia from –1.25 to –6.00 diopters. J Refract Surg 1997; 13:528–534

64. Pirzada WA, Kalaawry H. Laser in situ keratomileusis for myopia of (1 to (3.50 diopters. J Refract Surg 1997; 14(suppl):S425–S426

65. Buratto L, Ferrari M. Indications, techniques, results, limits and complications of laser in situ keratomileusis. Curr Opin Ophthalmol 1997; 8:59–66

66. Perez-Santonja JJ, Bellot J, Claramonte P, Ismail MM, Alio JL. Laser in situ keratomileusis to correct high myopia. J Cataract Refract Surg 1997; 23:372–385

67. Condon PI, Mulher M, Fulcher T, Foley-Nolan A, O'Keefe M. Laser intrastroma keratomileusis for high myopia and myopic astigmatism. Br J Ophthalmol 1997; 81:199–206

68. Marinho A, Pinto MC, Pinto R, Vaz F, Neves MC. Lasik for high myopia:

one-year experience. Ophthalmic Surg Lasers 1996; 27(suppl):S517–S520

69. Pallikaris IG, Siganos DS. Laser in situ keratomileusis to treat myopia: early experience. J Cataract Refract Surg 1997; 23:39–49

70. Kim HM, Jung HR. Laser assisted in situ keratomileusis for high myopia. Ophthalmic Surg Lasers 1996; 27(suppl):S508–S511

71. Helmy SA, Salah A, Badawy TT, Sidky AN. Photorefractive keratectomy and laser in situ keratomileusis for myopia between 6.0 and 10.00 diopters. J Refract Surg 1996; 12:417–421

72. Guell JL, Muller A. Laser in situ keratomileusis (LASIK) for myopia from (7 to (18 diopters. J Refract Surg 1996; 12:222–228

73. Fiander DC, Tayfour F. Excimer laser in situ keratomileusis in 124 myopic eyes. J Refract Surg 1995; 11(suppl):S234–S238

74. Salah T, Waring GO, el-Maghraby A, Moadel K, Grimm SB. Excimer laser in situ keratomileusis (LASIK) under a corneal flap for myopia of 2 to 20 D. Trans Am Ophthalmol Soc 1995; 93:163–190

75. Pallikaris IG, Siganos DS. Excimer laser in situ keratomileusis and photorefractive keratectomy for correction of high myopia. J Refract Corneal Surg 1994; 10:498–510

76. Brint SF, Ostrick DM, Fisher C, Slade SG, Maloney RK, Epstein R, et al. Six-month results of the multicenter phase I study of excimer laser myopic keratomileusis. J Cataract Refract Surg 1994; 20:610–615

77. Knorz MC, Liermann A, Seiberth V, Steiner H, Wiesinger B. Laser in situ keratomileusis to correct myopia of (6 to (29.00 diopters. J Refract Surg 1996; 12:575–584